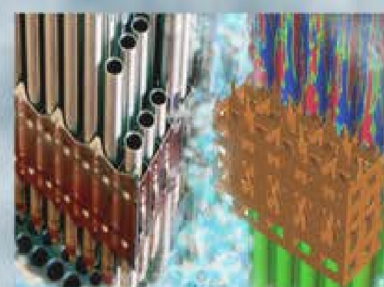
CASL-U-2015-0026-000

Fuel Performance with BISON



Koroush Shirvan
Massachusetts Institute of Technology

July 12, 2014

CASL-U-2015-0026-000

CANES
MIT Center for
Advanced Nuclear Energy Systems

CASL
Consortium for Advanced Simulation of LWRs

Fuel performance with BISON

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June 12, 2014

NSE
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science : systems : society

CASL-U-2015-0026-000

Outline

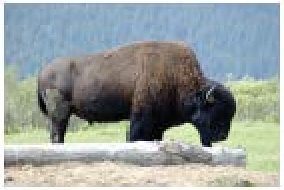
- BISON Overview
- Prerequisite
- Fuel Performance Overview
- Oxide Fuel Pin Behavior
- Reactivity Initiating Accidents
- Metal Fuel Pin Behavior
- BISON Demonstration
- Conclusions

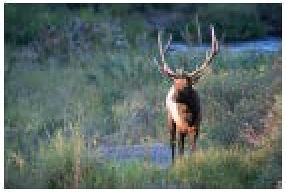
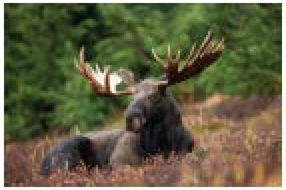
Main References:

22.251 2011 Class notes <https://stellar.mit.edu/S/course/22/fa11/22.251/index.html>
Karahan A. 2007. MIT PhD Thesis <http://dspace.mit.edu/handle/1721.1/57693>
NUREG-CR-7022 < http://pbadupws.nrc.gov/docs/ML1110/ML11101A005.pdf>
Shirvan K. paper 14298 ICAPP '14 <http://icapp.ans.org/icapp14/program/index.html>

BISON Overview

- BISON is a nuclear fuel performance analysis tool.
  - It is fully implicit, coupled and runs in parallel
  - It is still under development by INL, NEAMS and others
  - BISON is the non-propriety version of Peregrine and is related to MOOSE (Framework), Fox (material Properties), ELK (Structural Mechanics)
  - MOOSE takes advantage of generalized linear and nonlinear solvers, including PETSC and LibMesh.



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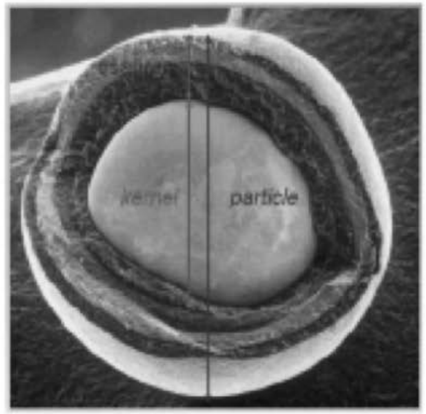
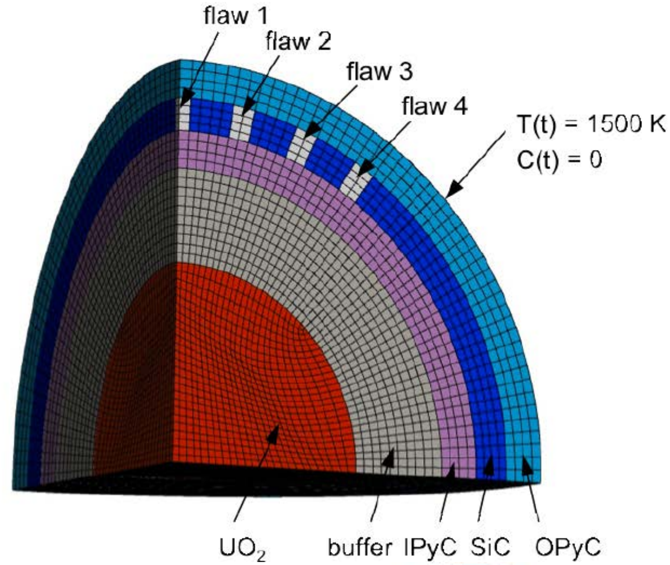
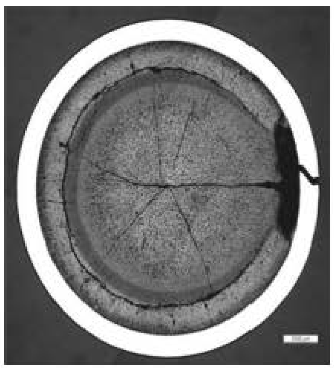
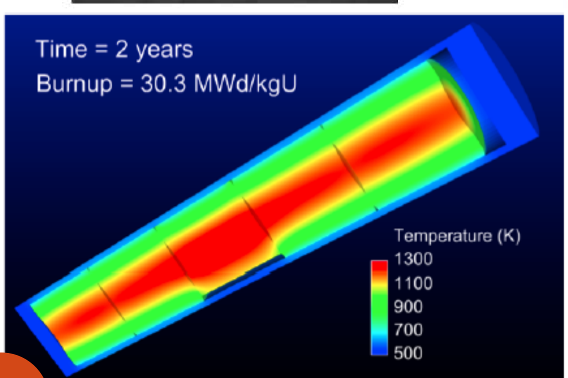
- BISON 3D fuel performance capability is *unique*

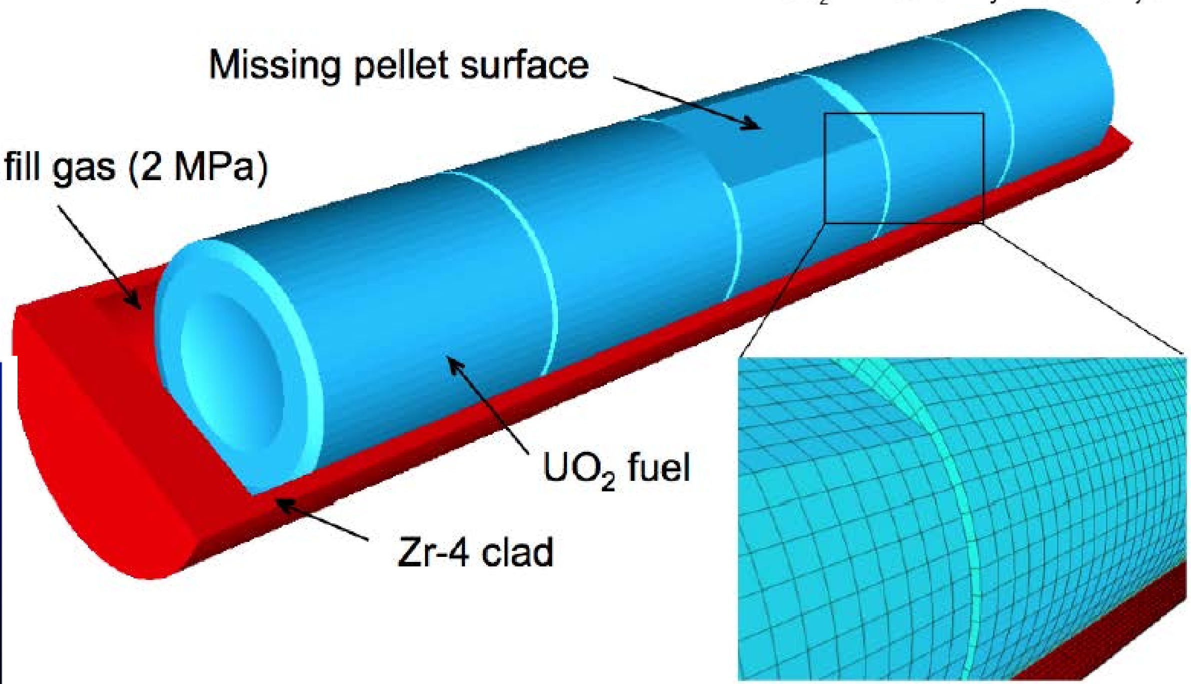






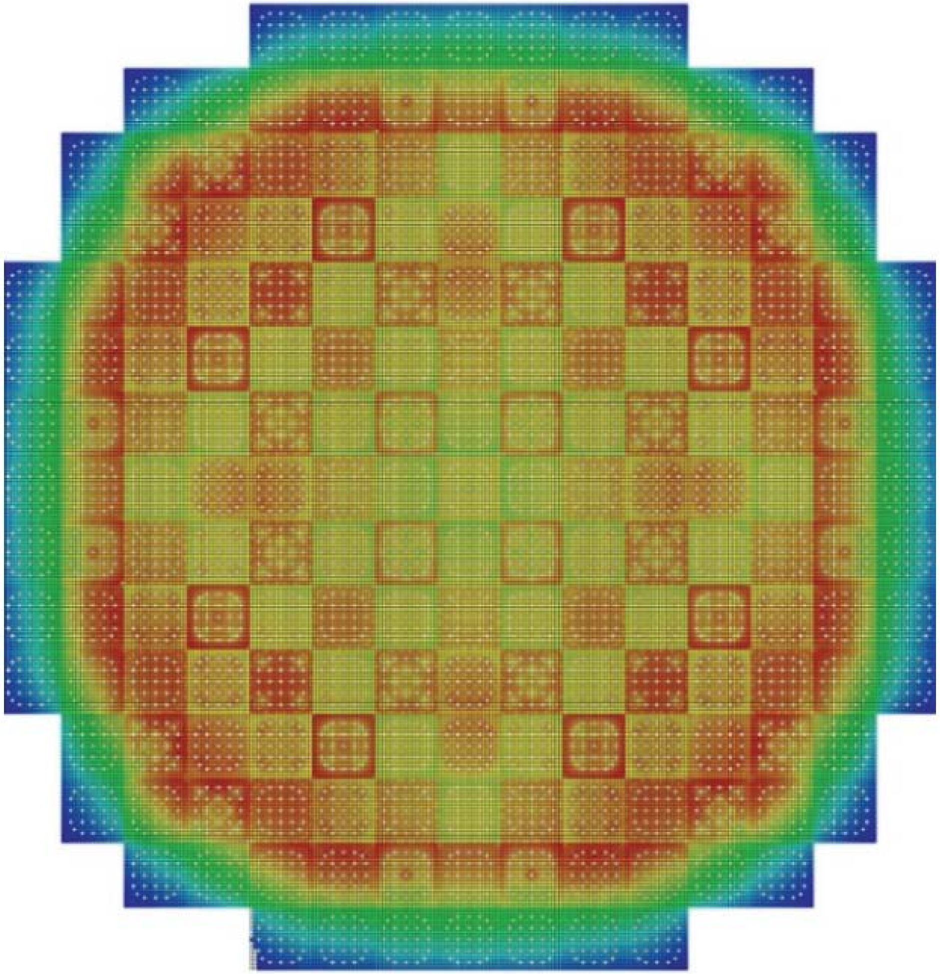


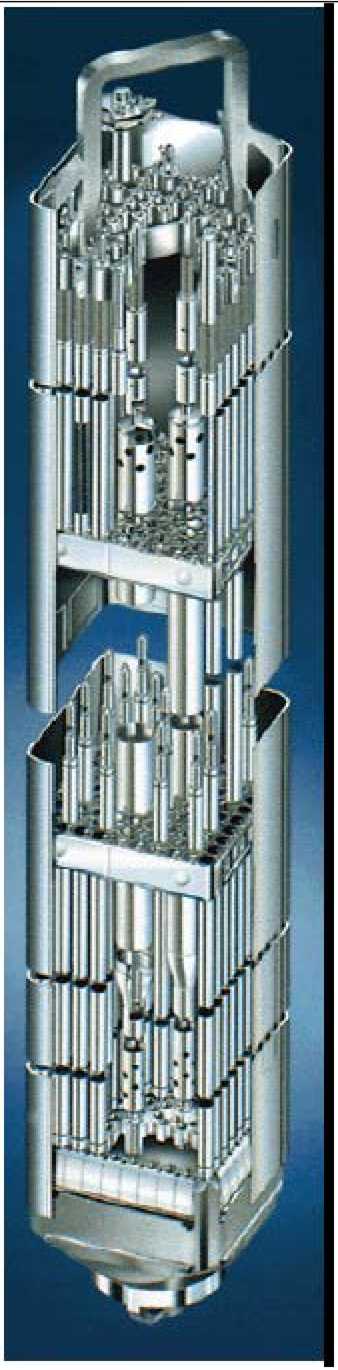
Fuel Temperature



* From BISON Workshop, 2012

Prerequisite





PWR Fuel Assemblies

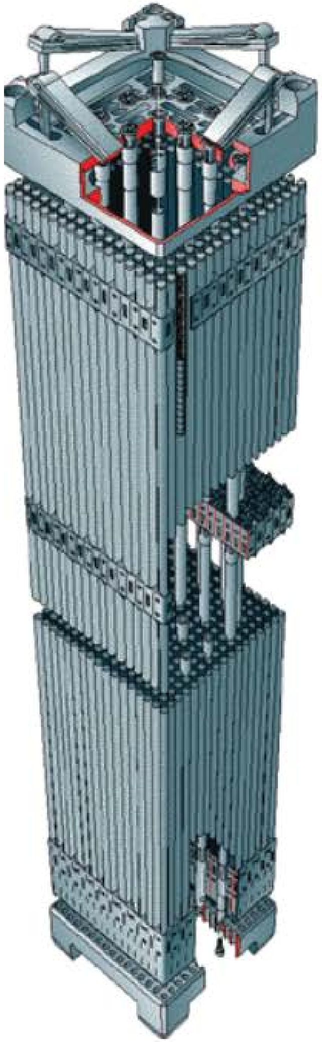
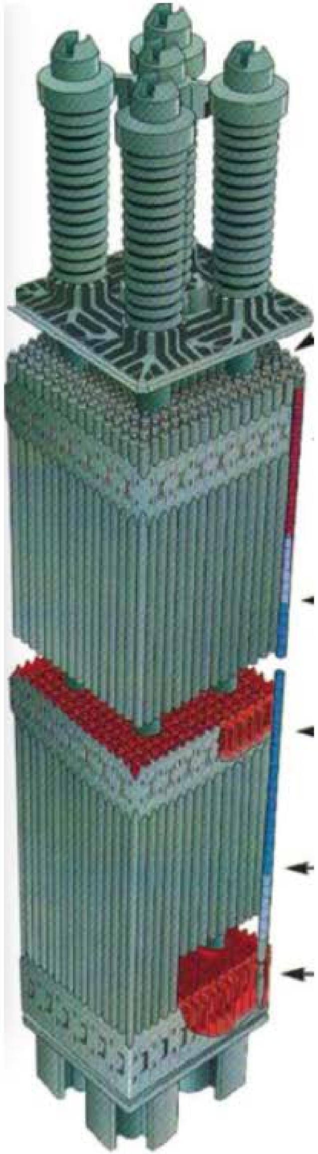


Table 11-3. Key Design Parameters of PWR Fuel

Item	Westinghouse 17x17 FA	ABB CE 16x16 FA
-Fuel Assembly Length	4063mm	4527mm
-Fuel Assembly Width	214mm	207mm
-Number&Material of Grids	#:8 Top/Bottom:Inconel Mid:Zry-4	#:11 Bottom:Inconel Top&Mid:Zry-4
-Number&Material of Intermediate Flow Mixers	#:3, Material:Zry-4	Not Applicable
-Number&Material of Guide Thimbles	#:24, Material:Zry-4	#:4, Material:Zry-4
-Number&Material of Instrumentation Tube	#:1, Material:Zry-4	#:1, Material:Zry-4
-Number&Type of Top Nozzle Springs	#:4, Type:Leaf Spring	#:4, Type:Coil Spring
-Fuel Rod Pitch	12.60mm	12.85mm
-Number of Fuel Rods	264	236
-Fuel Rod Length	3860mm	4093mm
-Pellet Stack Length	3658mm	3810mm
-Pellet Outer Diameter	8.19mm	8.26mm
-Pellet Length	9.83mm	9.91mm
-Pellet Density	95%TD	95%TD
-Clad Inner/Outer Diameter	8.36/9.50mm	8.43/9.70mm



MNF 三菱原子燃料株式会社

Mitsubishi Nuclear Fuel CO.,LTD.

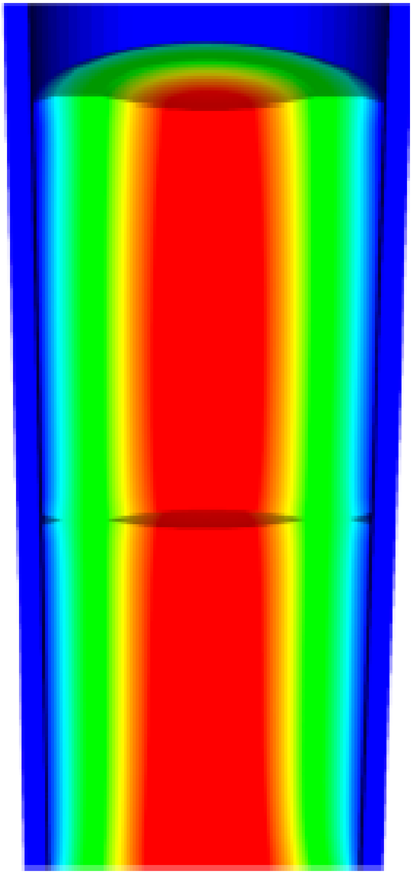
Zirconium Cladding Alloys

Alloy	Sn, %	Nb, %	Vendor (country)	Component	Reactor type
Zircaloy 2	1.2–1.7	–	All vendors	Cladding, structural components	BWR, CANDU
Zircaloy 4	1.2–1.7	–	All vendors	Cladding, structural components	BWR, PWR, CANDU
ZIRLO	0.7–1	1	Westinghouse	Cladding	PWR
Zr Sponge	–	–	Japan and Russia	Cladding	BWR
ZrSn	0.25	–	Westinghouse	Cladding	BWR
Zr2.5Nb	–	2.4–2.8	–	Pressure tube	CANDU
E100	–	0.9–1.1	Russia	Cladding	RBMK
E125	–	2.5	Russia	Pressure tube	RBMK
E635	0.8–1.3	0.8–1	Russia	Structural components	RBMK
M5	–	0.8–1.2	Areva	Cladding, structural components	PWR

*ZIRLO stands for **zir**conium **lo**w **o**xidation.

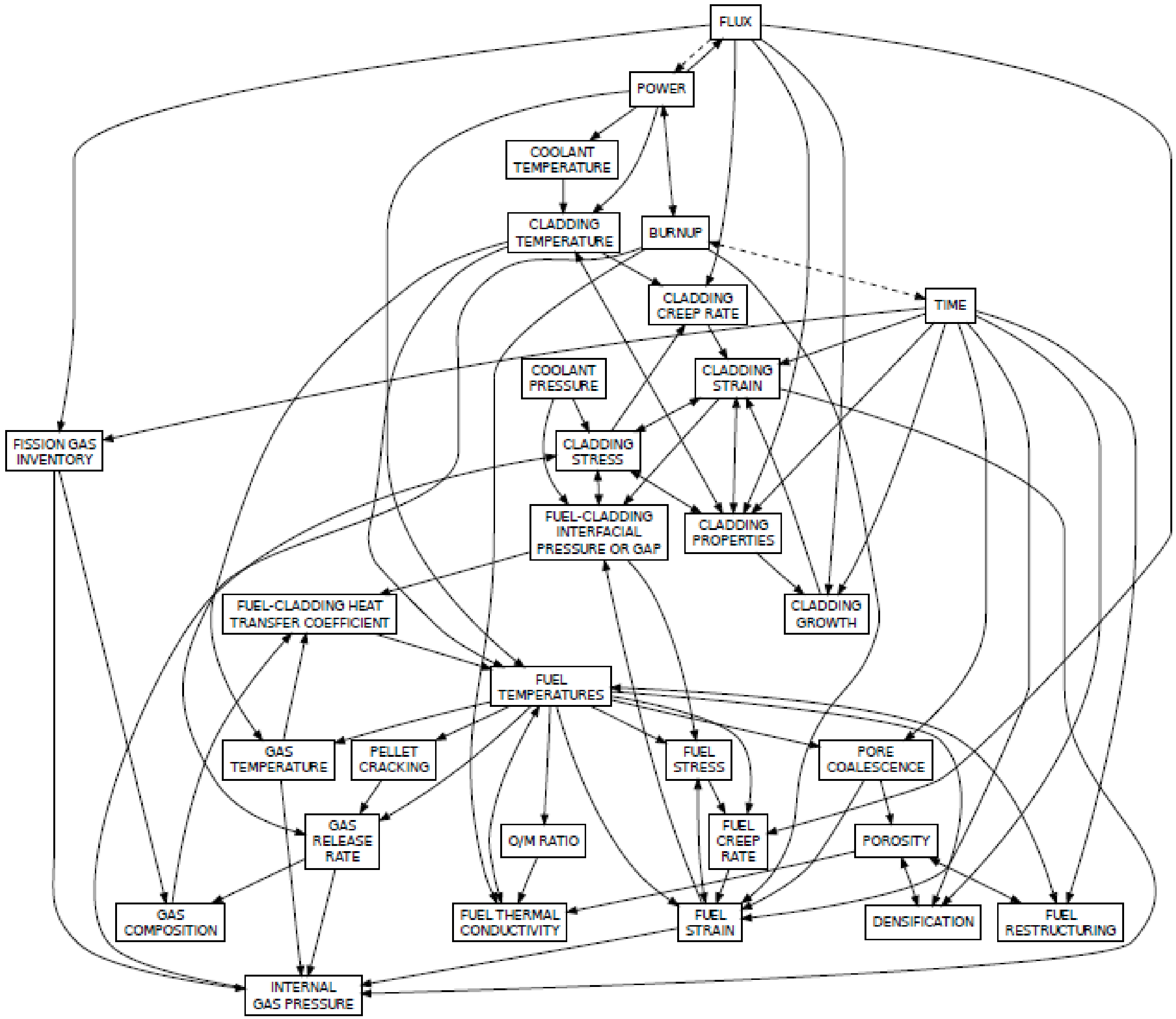
Fuel Performance Overview

- LWR Fuel performance modeling is divided into four general categories:
  - Fuel thermal response
  - Fuel mechanical response
  - Fission gas release and internal gas pressure response
  - Waterside corrosion.
- BISON is capable of modeling both in 2D and 3D
  - Only axisymmetric 2D capability was used in this study.



Temperature

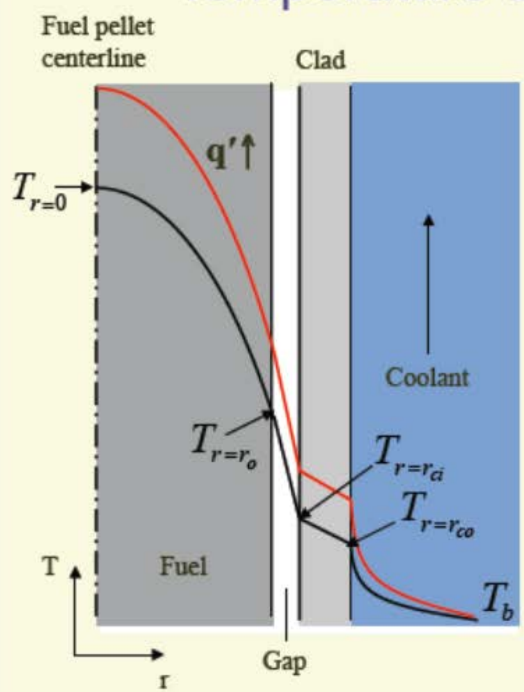
Fuel Performance Overview



Lassmann, J. Nuc. Mat., 57, 17 (1980)

Fuel Pin Heat Conduction Review

Temperature distribution in the fuel rod



$$T_{r=r_{co}} = T_b + \frac{q'}{2\pi\, r_{co} h}$$

Coolant heat transfer coefficient

$$T_{r=r_{ci}} = T_{r=r_{co}} + \frac{q'}{2\pi\, k_c} \ln(r_{co} / r_{ci})$$

Clad thermal conductivity

$$T_{r=r_o} = T_{r=r_{ci}} + \frac{q'}{2\pi\, r_o h_{gap}}$$

Gap conductance

$$T_{r=0} = T_{r=r_o} + \frac{q'}{4\pi\, k_f}$$

Fuel thermal conductivity

Temperatures in fuel and clad depend strongly on q′

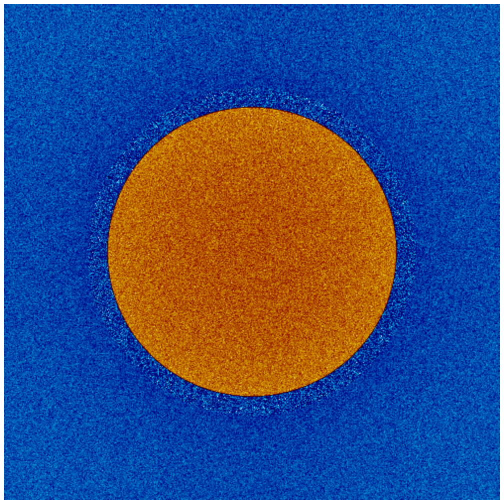
Why do we use Helium?

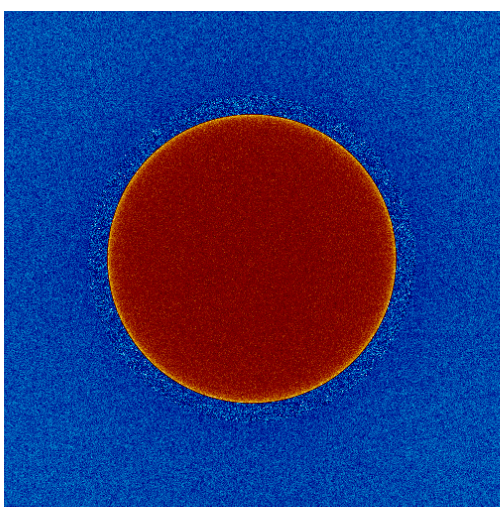
- Helium is very Conductive and inert
- However, as the fuel burns Krypton and Xenon are produced.

Units are milliwatts per meter kelvin.

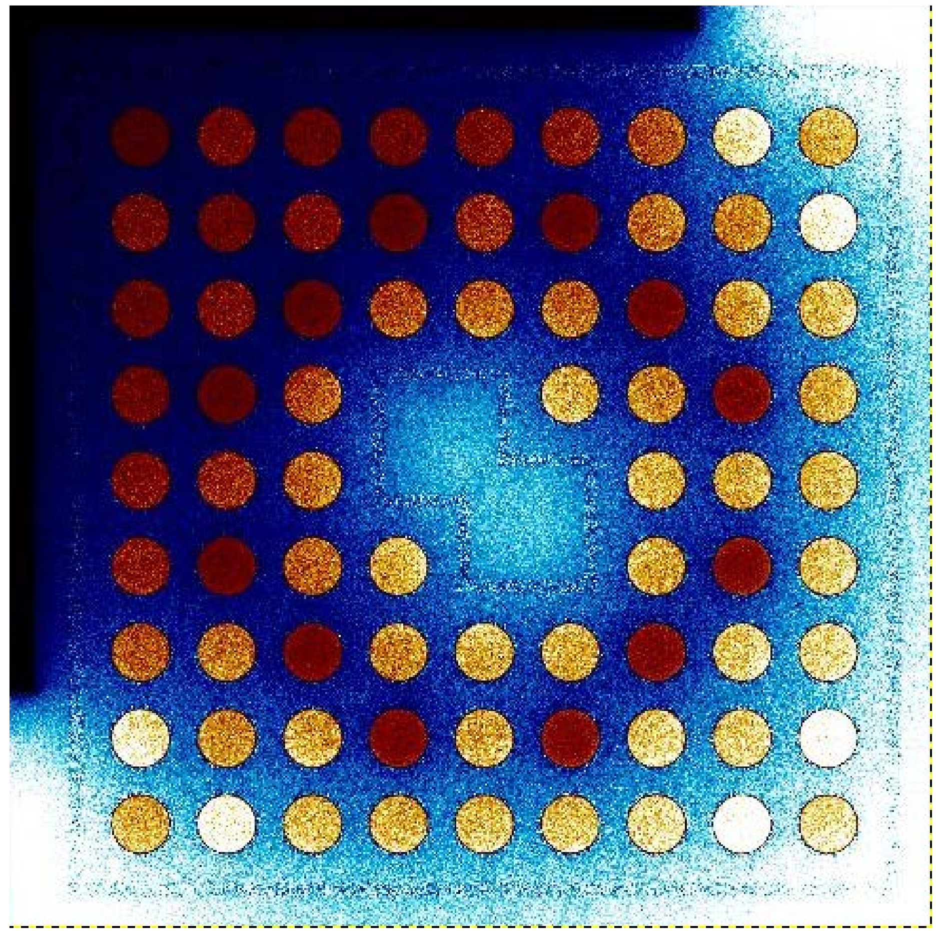
	Name	100 K	200 K	300 K	400 K	500 K	600 K
-	Air	9.4	18.4	26.2	33.3	39.7	45.7
Ar	Argon	6.2	12.4	17.9	22.6	26.8	30.6
H_2	Hydrogen (P = 0)	68.6	131.7	186.9	230.4	-	-
H_2O	Water	-	-	18.7	27.1	35.7	47.1
H_2S	Hydrogen sulfide	-	-	14.6	20.5	26.4	32.4
H_3S	Ammonia	[illegible]	[illegible]	24.4	37.4	51.6	66.8
He	Helium (P = 0)	75.5	119.3	156.7	190.6	222.3	252.4 8
Kr	Krypton (P = 0)	3.3	6.4	9.5	12.3	14.8	17.1
NO	Nitric oxide	-	17.8	25.9	33.1	39.6	46.2
N_2	Nitrogen	9.8	18.7	26.0	32.3	38.3	44.0
N_2O	Nitrous oxide	-	9.8	17.4	26.0	34.1	41.8
Ne	Neon (P = 0)	22.3	37.6	49.8	60.3	69.9	78.7
O_2	Oxygen	9.3	18.4	26.3	33.7	41.0	48.1
O_2S	Sulfur dioxide	-	-	9.6	14.3	20.0	25.6
Xe	Xenon (P = 0)	2.0	3.6	5.5	7.3	8.9	10.4
CCl_2F_2	Dichlorodifluoromethane	-	-	9.9	15.0	20.1	25.2
CF_4	Tetrafluoromethane (P = 0)	-	-	16.0	24.1	32.2	39.9
CO	Carbon monoxide (P = 0)	-	-	25.0	32.3	39.2	45.7

Fuel Radial Power Evolution: High Fidelity Neutronics can help

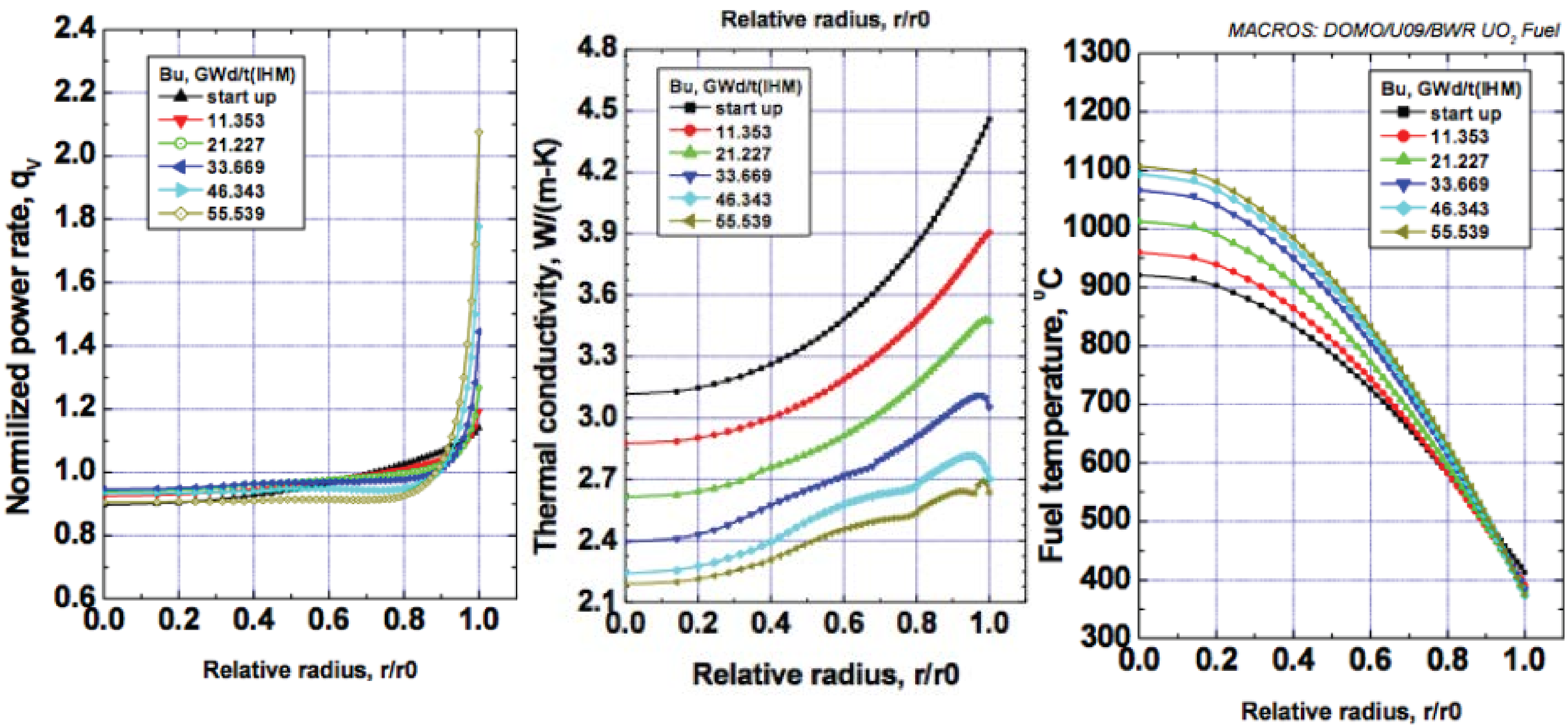




UO_2 (5% U^{235})



Pellet Thermal Response

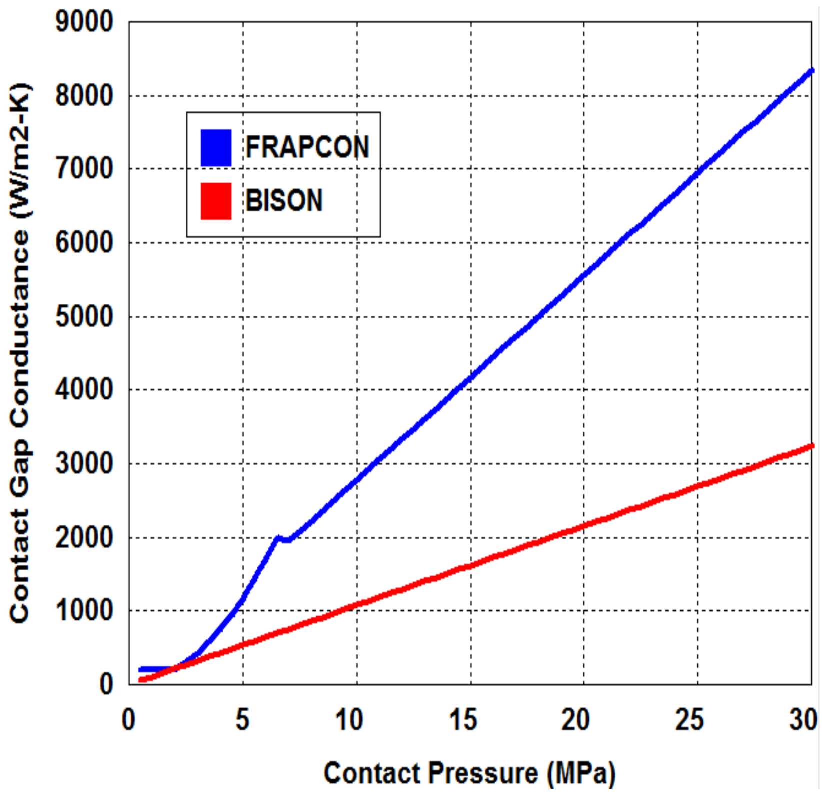


Fuel Thermal Performance

- For the coolant side, constant inlet temperature, mass flux and pressure along with the same rod diameter, pitch and heat transfer correlation.
- For the cladding thermal conductivity, FRAPCON uses temperature dependent function, while in BISON, a constant value of 16 W/m-K is assumed.
- For the fuel thermal conductivity, the NFI model with identical input variables such as theoretical density is used in both codes.
- The widely used, TUBRNP radial power profile model is used in both codes as well.
- The plenum gas temperature:
  - FRAPCON: is approximated based on the energy transfer between the top of the pellet stack and plenum gas as well as coolant to the upper plenum, in addition to rate of gamma heating.
  - BISON: since the plenum volume is not meshed, the pellet surface temperature is an averaged temperature of the cladding interior and pellet exteriors finite element nodes.

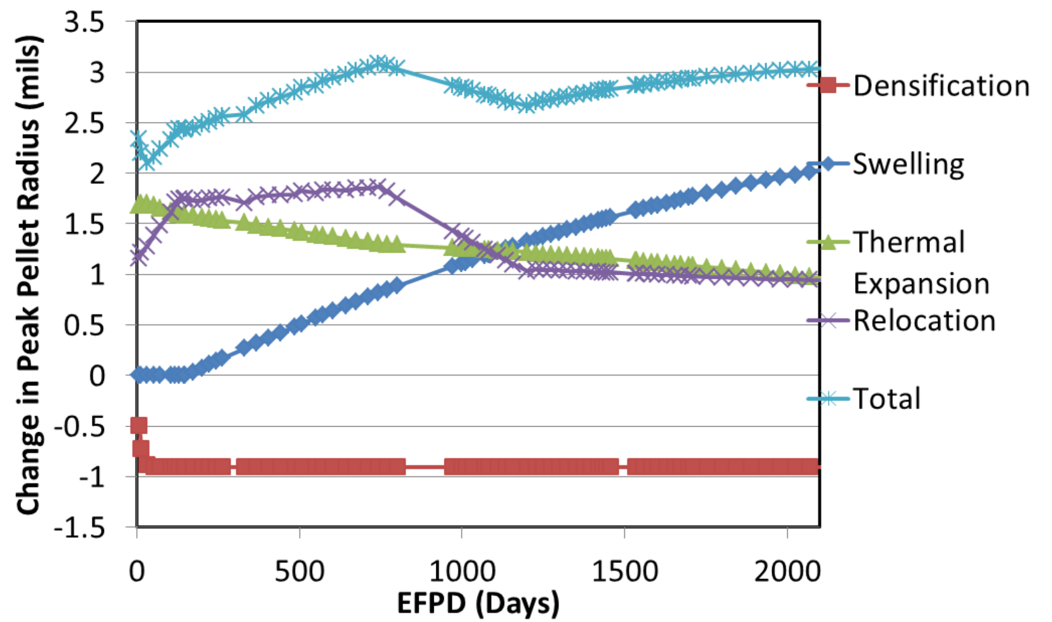
Fuel Thermal Performance - Gap

- The gap conductance has three components:
  - Conduction due to radiation: Same for both codes
  - Conduction through the gas: Similar models accounting for 7 different gases with BISON utilizing temperature dependent coefficients
  - Conduction through the fuel-cladding contact: Same formulation (Mikic-Todreas) but BISON model is based on a more limited database



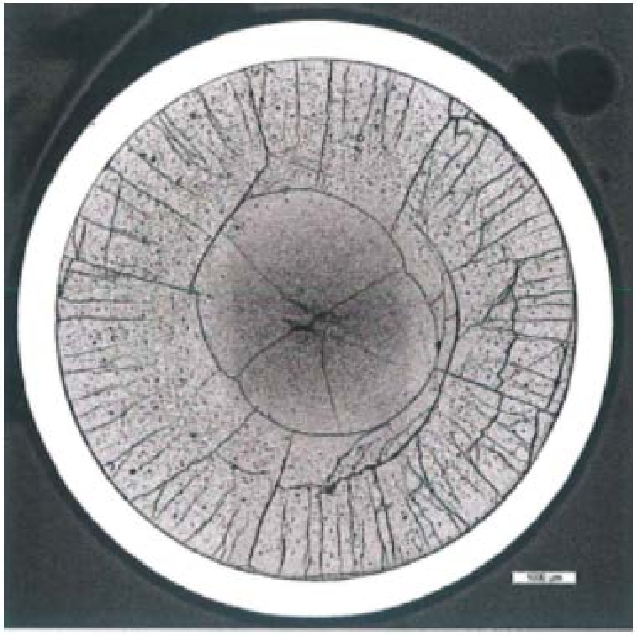
Fuel Mechanical Response

- There are four mechanisms considered in pellet mechanical response that are sources of strain:
  1. Relocation (typically not considered axially)
  2. Fuel Thermal Expansion
  3. Swelling
  4. Densification

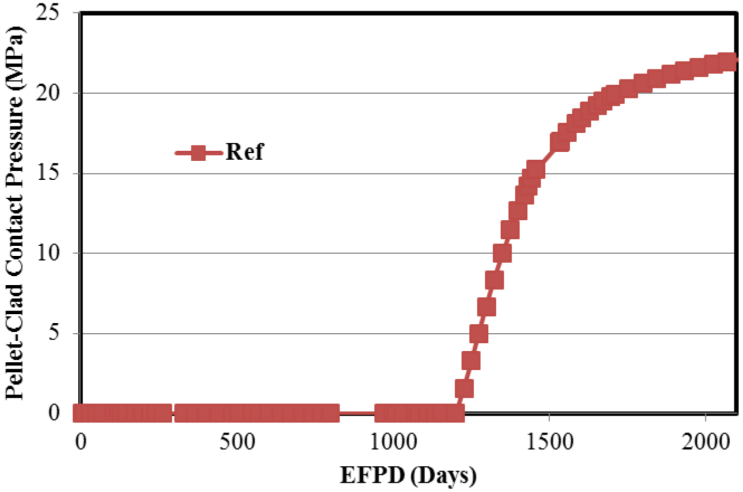


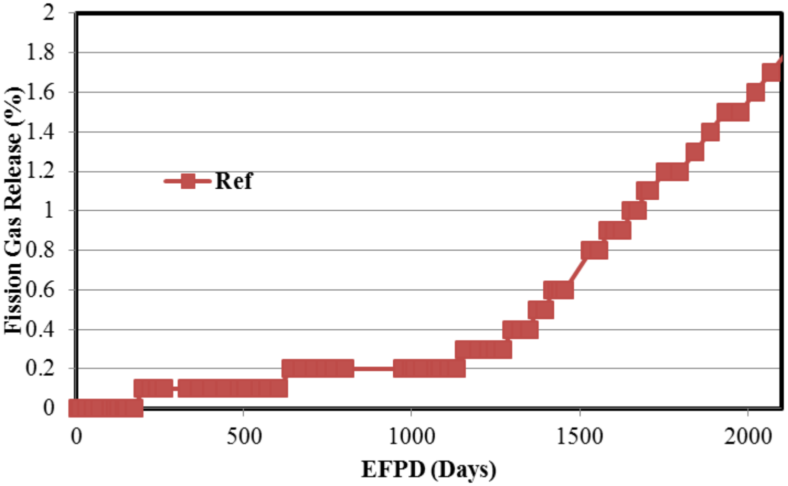
Pellet Mechanical Response

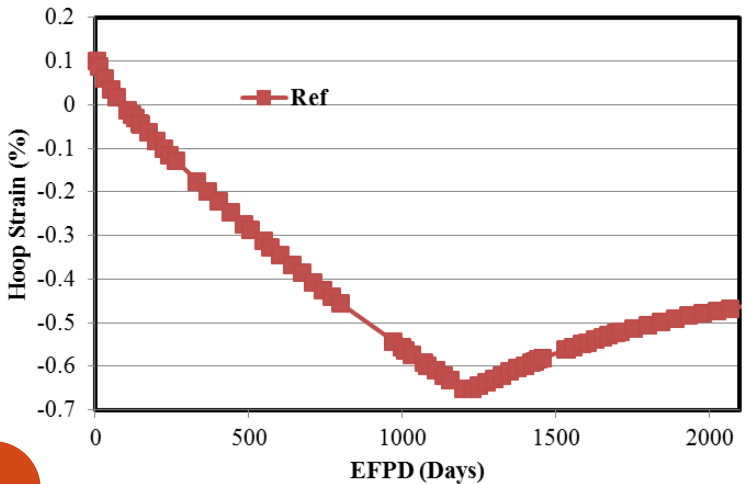
- As the fuel temperature increases, the extreme stresses resulting from the large temperature gradients in the fuel cause the fuel to crack (predominantly radial) and relocate.
- A central void could be formed due to fuel restructuring that includes the migration of as-fabricated porosity and grain growth.

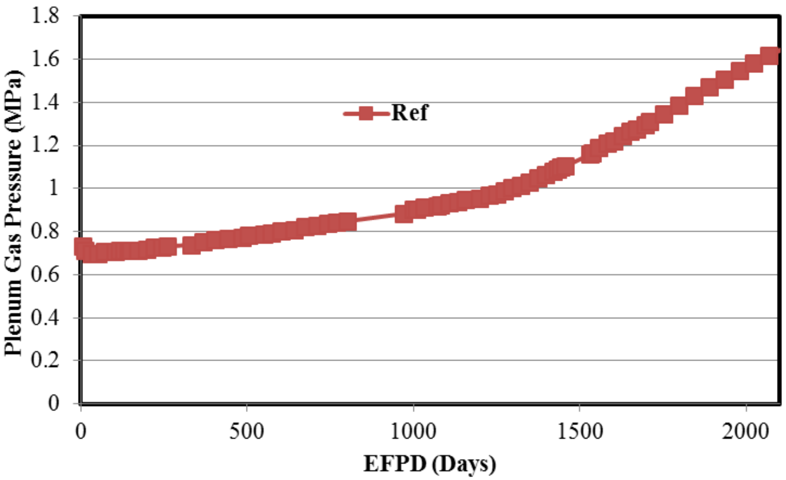


Fuel Rod Performance

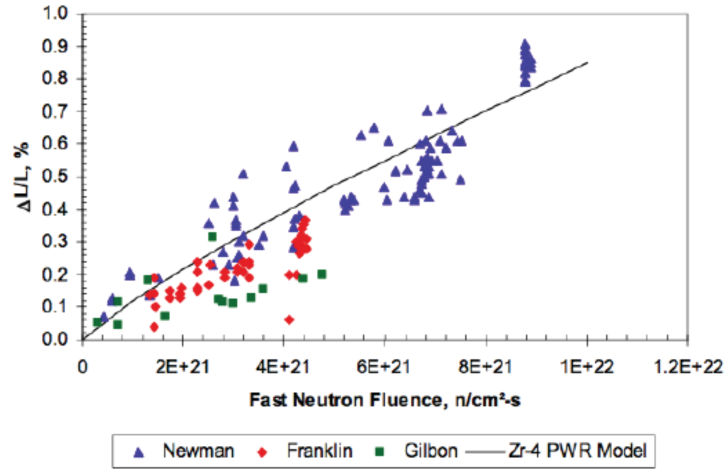


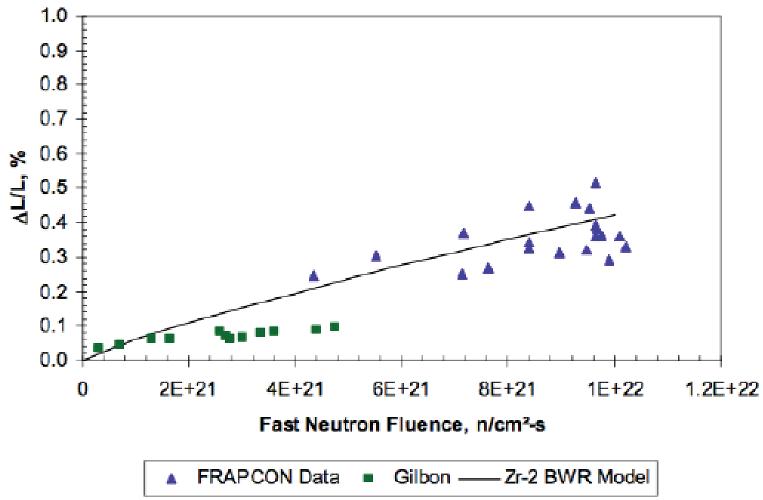


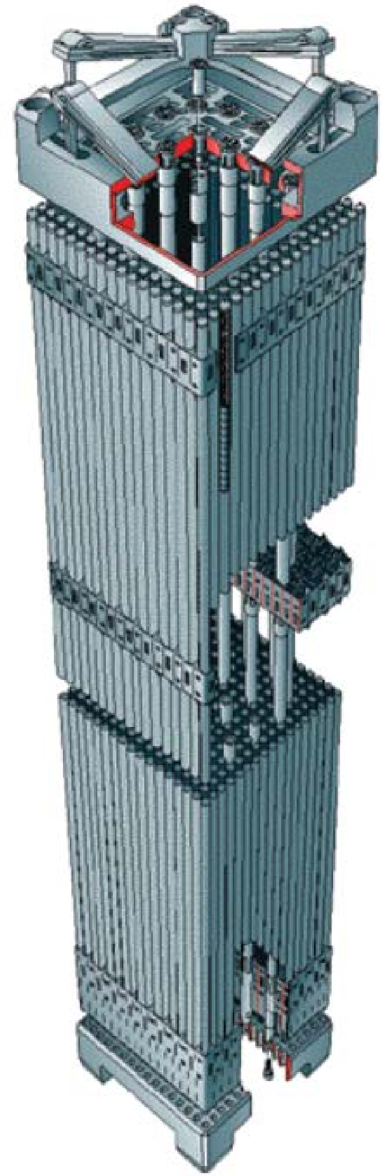




Fuel Rod Axial Growth





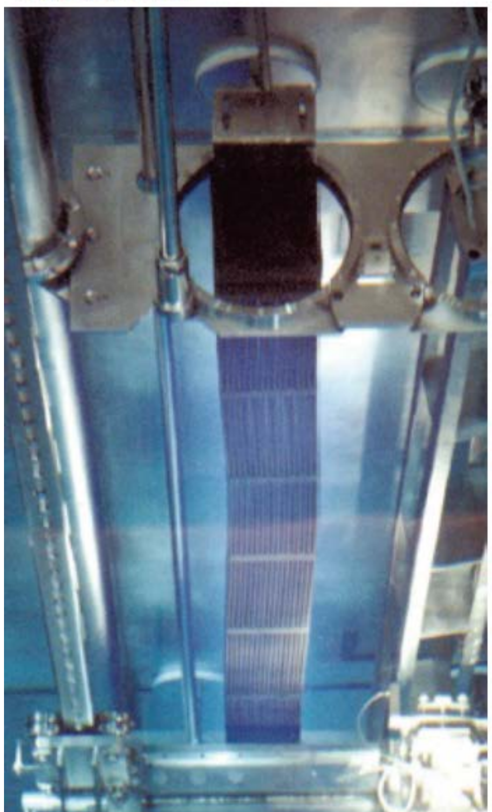


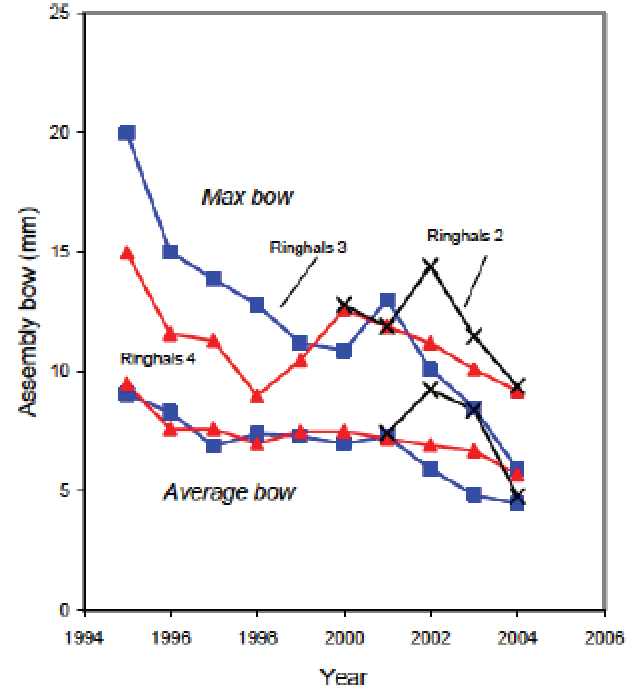
Fuel Rod Bowing

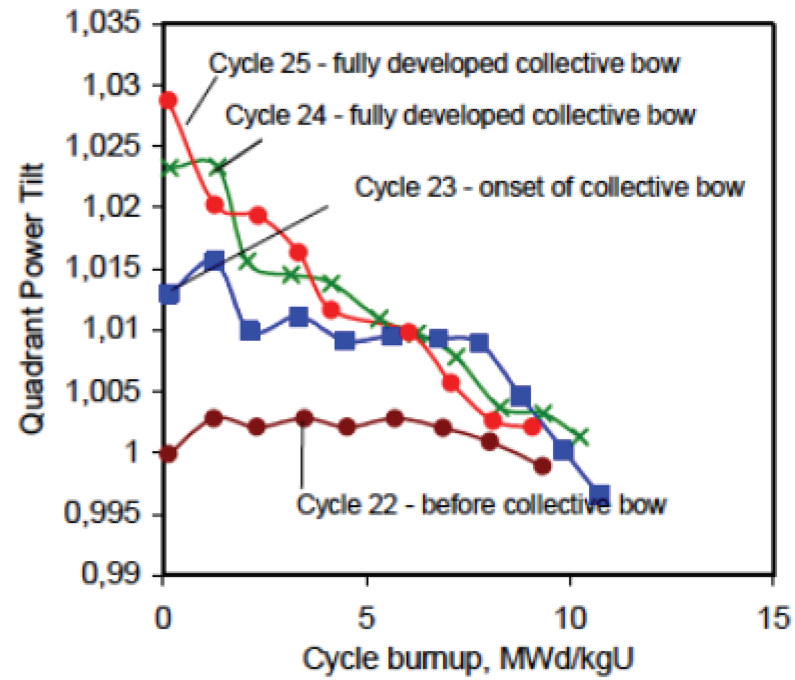
A DECADE OF ASSEMBLY BOW MANAGEMEN

T. ANDERSSON
Ringhals AB,
Väröbacka, Sweden

J. ALMBERGER, L. BJÖRNKVIST
Vattenfall Bränsle AB,
Stockholm, Sweden





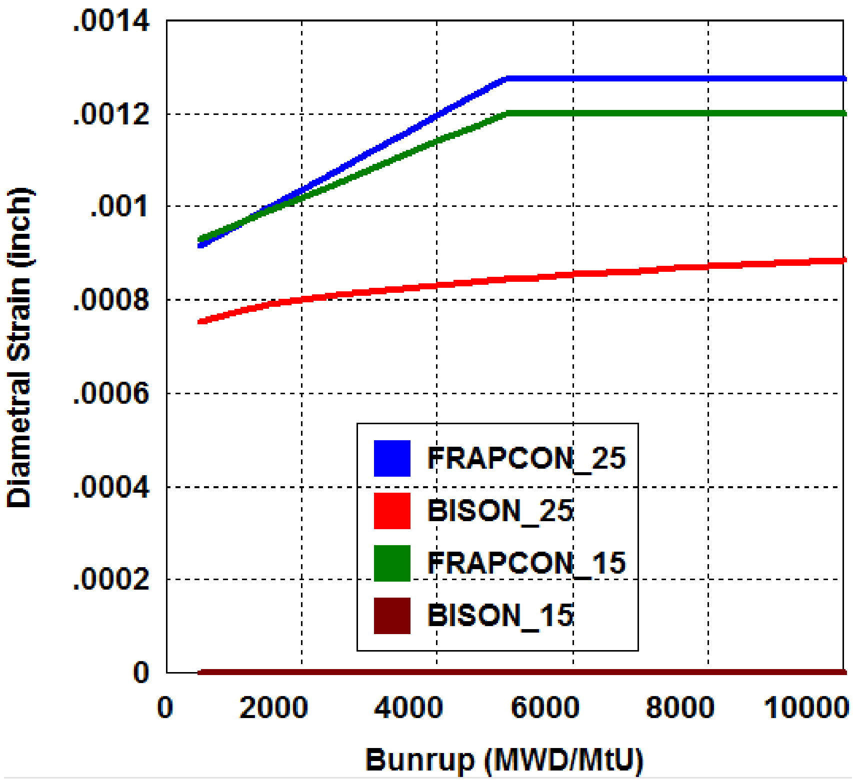


Fuel Mechanical Response

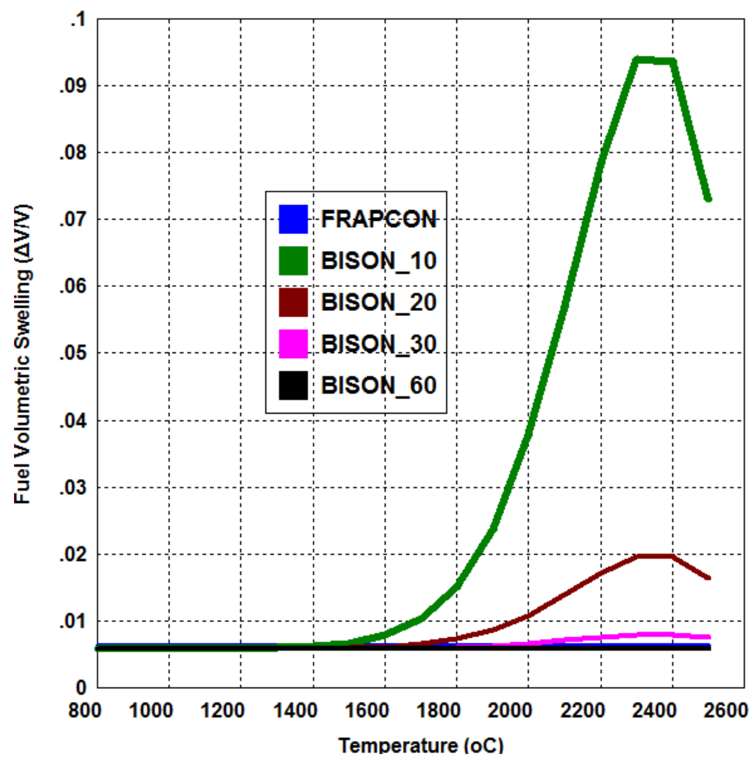
- FRAPCON utilizes "rigid pellet model" as well as the "thick shell" cylinder approximation with uniform temperature.
- In BISON, both the fuel and cladding are descriticized in finite elements and the stress is calculated in each node.
- 2D axisymmetric smeared analysis is utilized in both codes
    - Assume that both the fuel and clad deforms in a manner of retaining its cylindrical shape
- In most fuel performance codes the fuel outer diameter is determined through densification, relocation, swelling models as well as thermal expansion.

Fuel Mechanical Response-pellet

- Similar densification models except at higher than 750 °C, BISON depends on temperature: higher rate than FRAPCON



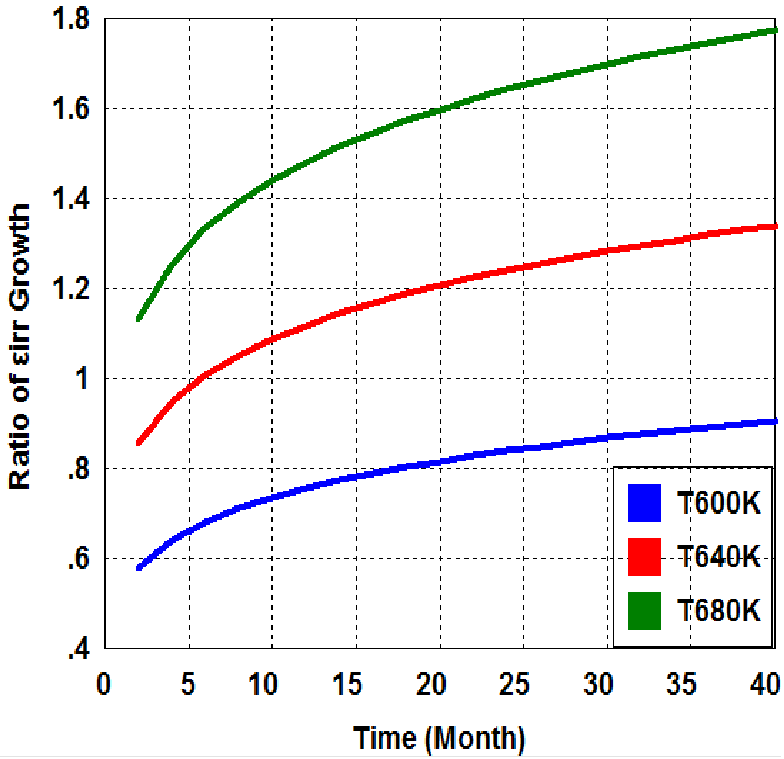
The comparison of relocation strain model at 25 and 15 kW/m LHGR.



The comparison of swelling models at 10, 20, 30 and 60 MWd/kgU

Fuel Mechanical Response

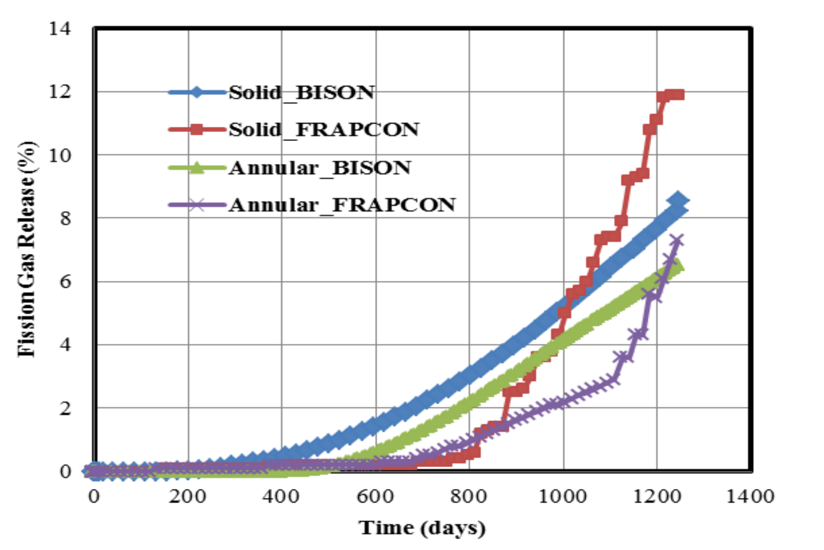
- The fuel axial creep is modeled in BISON using MATPRO FCREEP material model accounting for secondary creep and irradiation creep.
  - Such physics is completely neglected in FRAPCON.
  - This creep is proportional to volumetric fission rate and effective stress (von Mises).
- For the cladding, the primary and secondary creep are modeled similarly in both codes



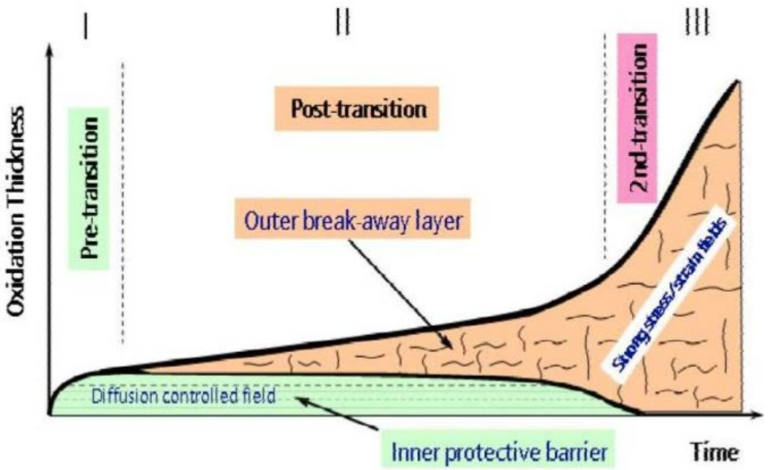
The ratio of the irradiation growth models in FRAPCON over BISON at a constant effective stress of 10 MPa.

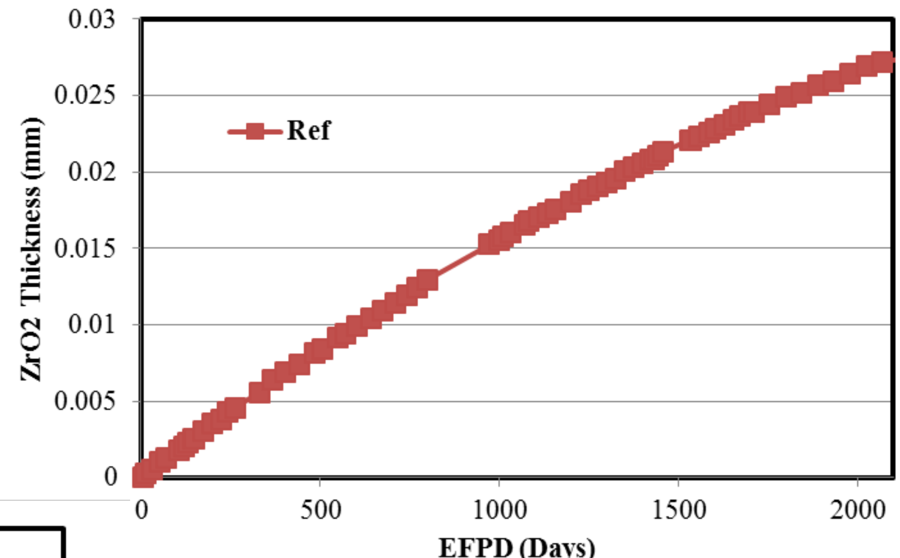
Internal Gas Pressure response

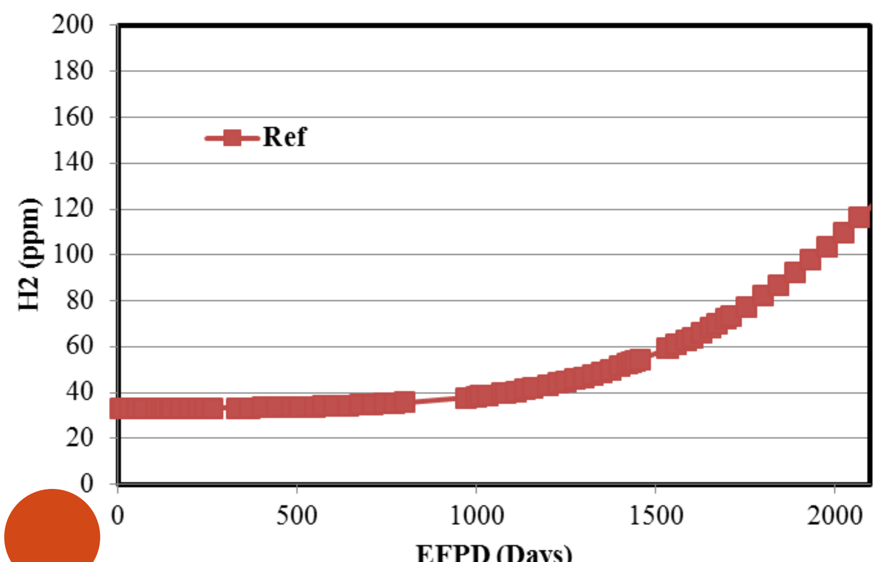
- While both codes utilize ideal gas law in the plenum, in the fuel "cracks", FRAPCON utilizes the average fuel temperature, while BISON uses the temperature in each finite element mesh.
- The rate for release of fission gases are estimated using the well-known, modified Forsberg-Massih Fission Gas Release (FGR) model in FRAPCON, while the Simple integrated fission gas release and swelling (Sifgrs) model, is used in BISON.
  - The Sifgrs model shows a smooth release of fission gases while the FRAPCON model involves steps and acceleration thresholds.



oxidation and hydrogen pickup



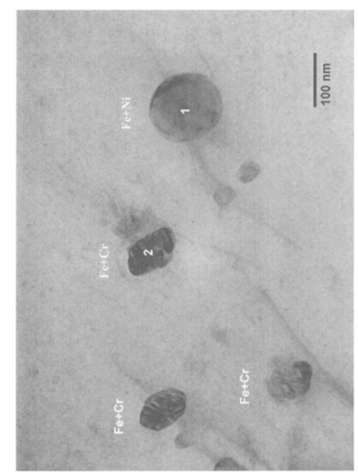




Second Phase Particles (SPPs) are critical for zirc-oxide protective properties

Dissolution with irradiation:

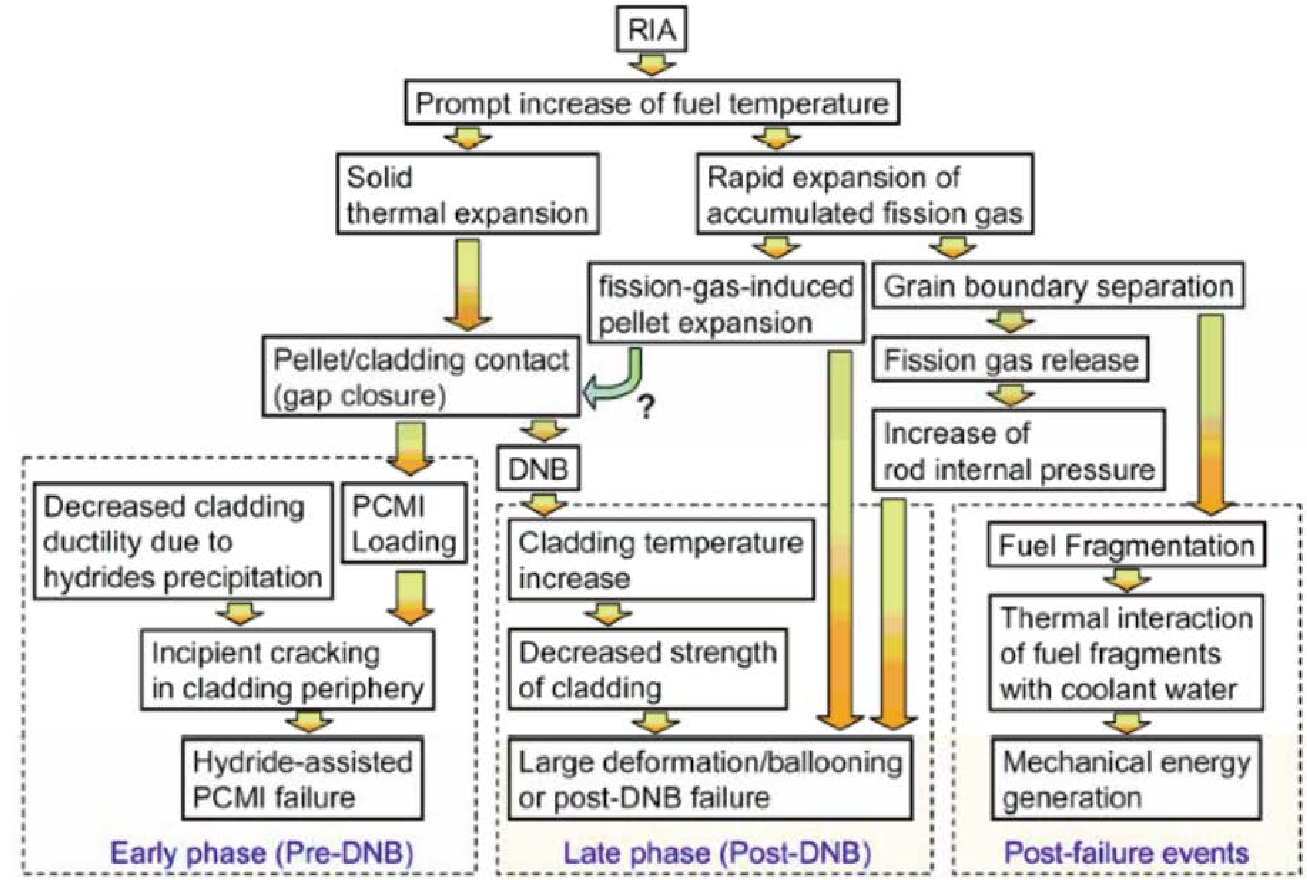
Leads to loss of zirc-oxide "barrier" layer



BISON Summary: For 2D Axisymmetric Smeared Simulations

- The current default version of BISON code can effectively model fuel performance of PWR rods.
- There were many models identified within BISON and FRAPCON that are different, but the EOL fuel temperature resulted in similar values.
  - This implies a *cancellation of inconsistencies* in both codes, which should be carefully studied with separate effect tests.
- Rather than its ability to perform fully coupled multi-physics simulation under finite elements, the framework of BISON, which allows addition of models and new geometry with high quality assurance, is deemed the strength of the code compared to FRAPCON and most of existing fuel performance codes.

Fuel Performance in Reactivity Initiation Accidents (RIAs)



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NEA/CSNI/R(2010)1

Fuel Performance in Reactivity Initiation Accidents (RIAs)

BEHAVIOUR OF HIGH BURNUP PWR FUELS DURING SIMULATED REACTIVITY-INITIATED ACCIDENT CONDITIONS

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Tokai-mura, Ibaraki-ken 319-1195 – Japan

Table 1. Fuel samples and test conditions in the VA-1, -2, MR-1 and RH-1

Test ID		VA-1	VA-2	MR-1	RH-1
Reactor which the fuel had been irradiated		Vandellos		McGuire + R2	Ringhals
Fuel type		17 x 17			
Cladding material		MDA	ZIRLO	NDA	M5
Initial enrichment	(%)	4.5	4.5	3.75	3.7
Pellet grain size	(μm)	~10	~10	~40	~10
Test rod sampling position (span from the bottom)		5th	5th	-	3rd
Test rod burnup	(MWd/kgU)	78	79	71	67
Cladding oxide thickness	(μm)	~73	~70	~39	~10
Date of pulse in the NSRR	(M/D/Y)	2/17/05	8/2/05	4/21/05	2/22/06
Peak fuel enthalpy	(J/g)	530*	540*	371	533
Peak fuel enthalpy	(cal/g)	127*	130*	89	127
Fuel enthalpy at failure	(J/g)	255	230	No failure	No failure
Fuel enthalpy at failure	(cal/g)	61	55		

* : Peak fuel enthalpy expected for no failure.

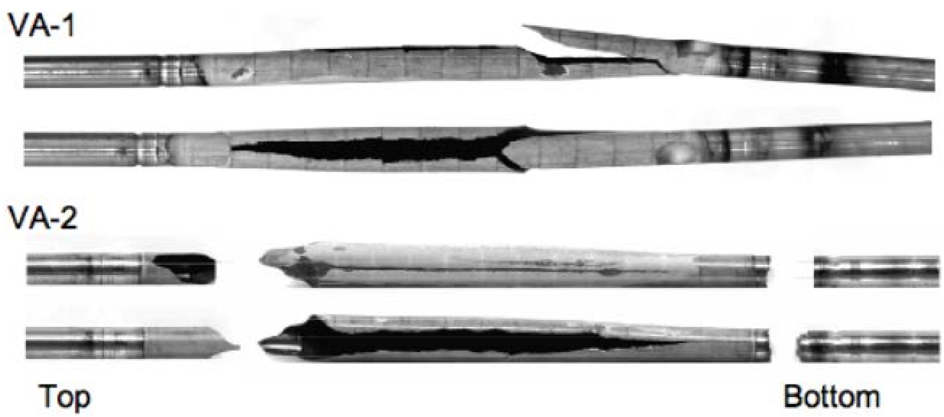
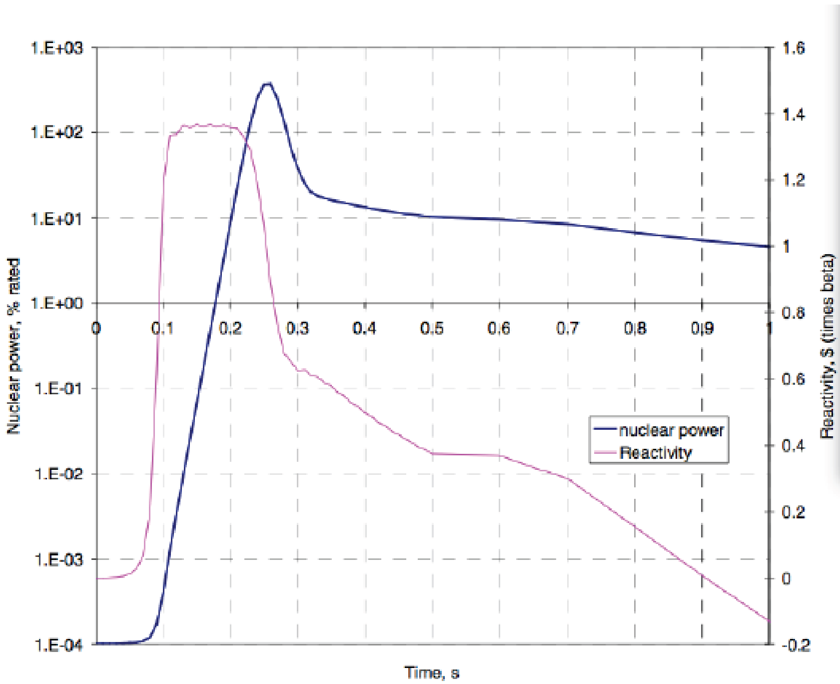
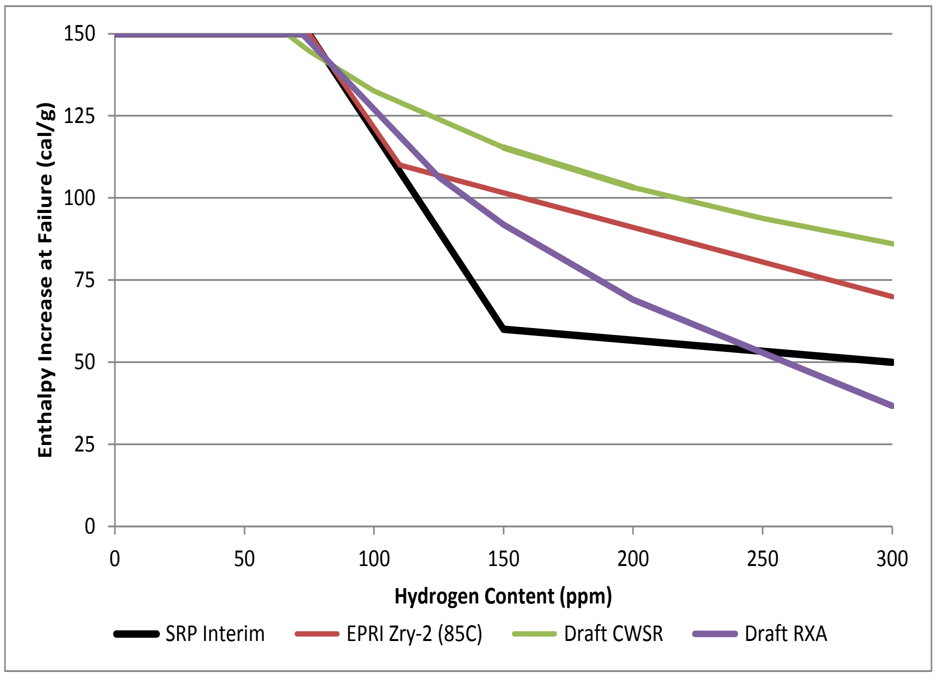


Fig. 1 Visual appearances of the post-test VA-1 and -2 rods.

Fuel Performance in Reactivity Initiation Accidents (RIAs)

- The new NRC guidelines on RIAs is based on cladding hydrogen content.



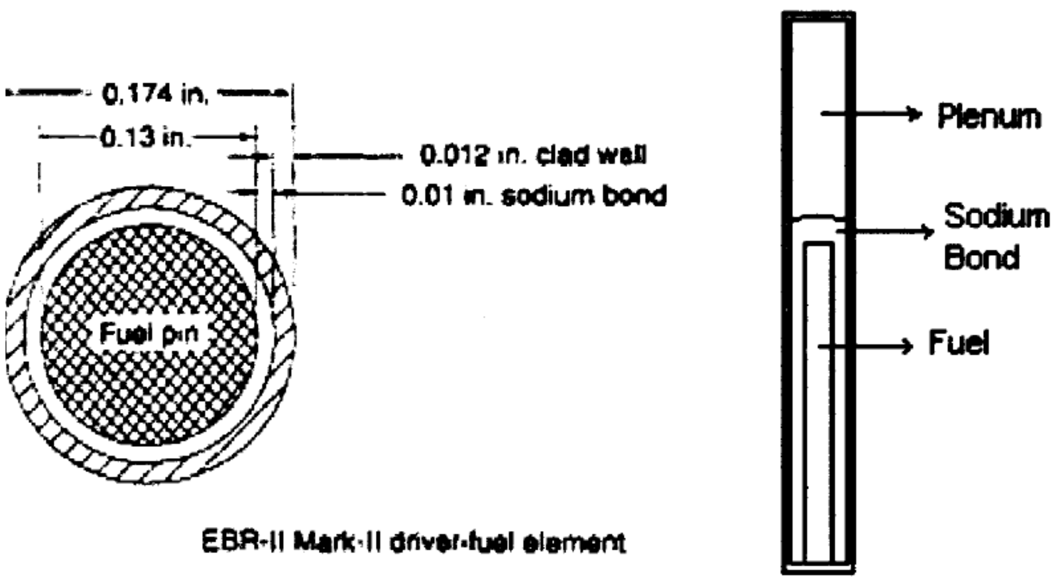


Going Beyond 62 MWD/kg Burnup

- **Category 1: Fuel System Damage**
  - Design Stress
  - Design Strain
  - Strain Fatigue
  - Fretting Wear
  - Oxidation
  - Hydriding
  - Crud
  - Rod Bow
  - Irradiation Growth
  - Internal Gas Pressure
  - Hydraulic Lift Loads
  - Fuel Assembly Lateral Deflection
- **Category 2: Fuel Rod Failure**
  - Internal Hydriding
  - Cladding Collapse
  - Fretting
  - Overheating of Cladding
  - Overheating of Fuel Pellets
  - Excess Fuel Enthalpy
  - Pellet/Cladding Interaction
  - Clad Rupture
  - Mechanical Fracturing
- **Category 3: Fuel Coolability**
  - Cladding Embrittlement
  - Violent Expulsion of Fuel
  - Generalized Clad Melting
  - Fuel Rod Ballooning
  - Structural Deformation

Metal Fuel

- The metallic fuels are commonly more used in Sodium reactor, especially in the United States.



Fuel	U-Pu-Zr
Gap	Liquid Sodium
Clad	HT9
Coolant	Liquid Sodium

Figure-1: Description of the metallic fuel

Metal Fuel- The Positive

- The attractive characteristics of metal fuel include:
  - High thermal conductivity, which combined with a highly conducting gap, maintains fuel temperatures low and reduces stored energy, an important feature during transients, such as the unprotected loss of primary flow and loss of heat sink.
  - High heavy metal density and low moderating power, which provide for a harder spectrum and excellent neutron economy.
  - Low Fuel Clad Mechanical Interaction (FCMI), which enables achievement of high burnup.
  - Good compatibility with the coolant (sodium).
  - Ease of manufacturing and reprocessing by pyro chemical methods.

Metal Fuel- The Negative

- However, various phenomena limit the in-core performance of metal fuel assemblies:
  - Low melting point
  - Thermal and irradiation creep
  - Fuel void swelling
  - Fuel restructuring
  - Fuel/Clad Chemical Interaction
  - Higher Hydrogen production if Zirconium based fuel is used.

Thermo-mechanical Behavior of the Metal Fuel

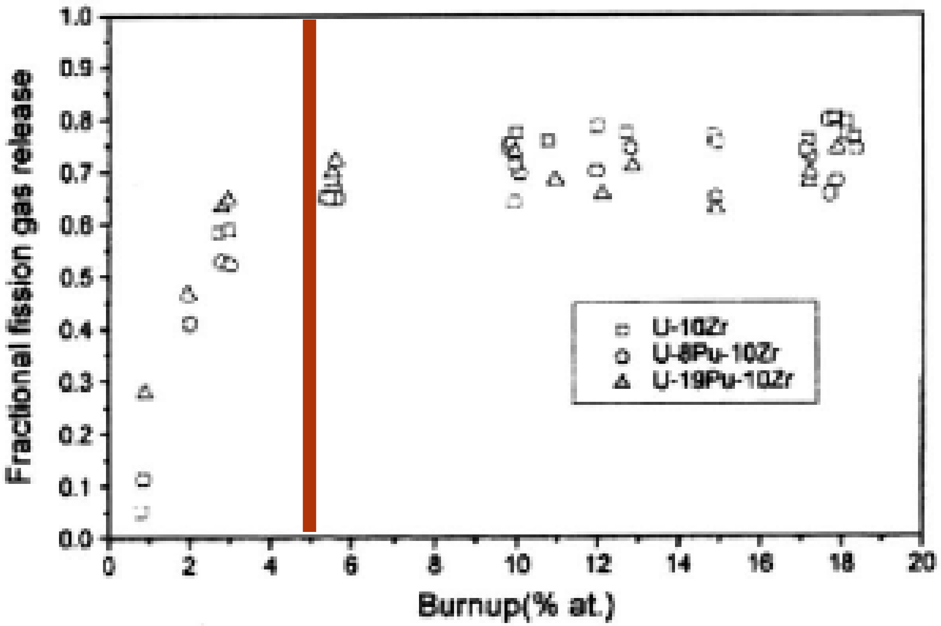
- Description of the burnup history (72 % smear density U-19Pu-OZr Fuel)

Burnup (at %)	Relevant phenomena
0.0	Irradiation begins
0.5-1.0	(1) Due to swelling, grain boundary tearing and cracking, the fuel reaches the clad and becomes axially restrained at the 'hot' axial location. (2) Resulting axial friction force is enough to stop the axial growth of the fuel by compressing the existing open gas pores. Furthermore, swelling rate reduces due to axial frictional force. (3) The radial contact pressure between fuel and clad is low due to extrusion of the inner zone fuel into the cracks. (4) Fission gas release into the plenum begins.
1.0-2.0	(1) Cracks are closed and fuel becomes both axially and radially restrained at the hot axial location. (2) Radial contact pressure between fuel and clad rises to a level somewhat higher than plenum pressure. Open gas pores start to be compressed to accommodate for solid/liquid fission product swelling. (3) Fission gas release fraction rises rapidly to 50 %.
2.0-13.0	Contact pressure holds at a level somewhat higher than the plenum pressure as the open pores are further compressed to accommodate accumulation of solid products.
13-20	Fuel does not have enough open pores to accommodate solid fission product accumulation. The resulting fuel-clad contact pressure rises significantly. When open pores are less than 5 %, the contact pressure rises rapidly and breach may result.

Metal Fuel: Fission Gas Release

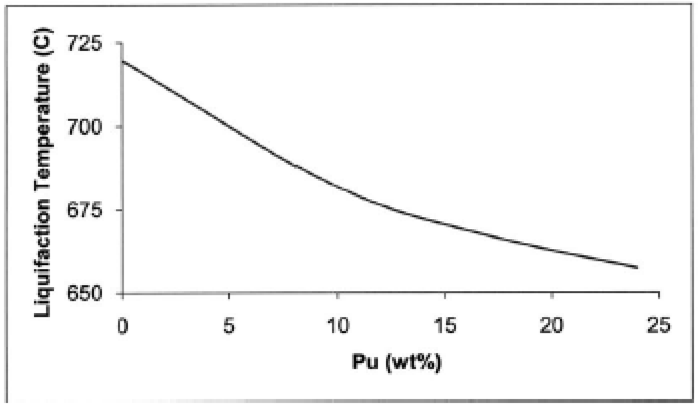
Comparison of metal and oxide fuel diffusion coefficients (m^2/s)

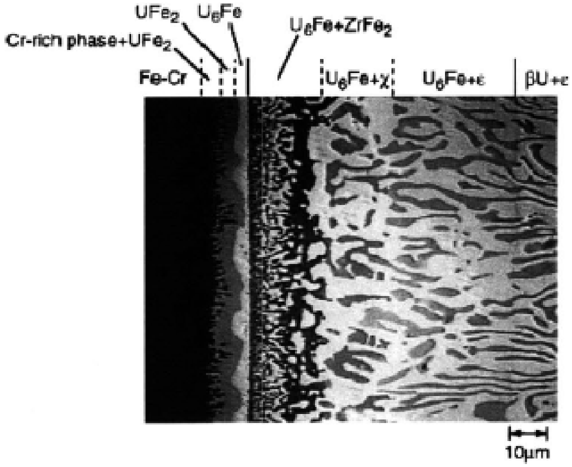
Temperature (K)	Metal Fuel (FEAST)	UO_2 Fuel* [32]
1000	9.9E-15	6.0E-21
900	5.4E-16	6.0E-21
800	1.4E-17	6.0E-21
700	1.3E-19	6.0E-21



Metal Fuel: Fuel Clad Chemical Interaction

- During the steady state irradiation, the cladding constituents may diffuse into the fuel and form a low-melting point alloy (eutectic).
- As the burnup increases, some fission products diffuse into the cladding to form low-melting phases with iron that creates a brittle band, containing numerous cracks.
- Within these phases, (U,Pu) 6Fe layer within the outer surface of the fuel has low melting point
- The presence of zirconium in the fuel decreases Fuel/Cladding Chemical Interaction significantly.

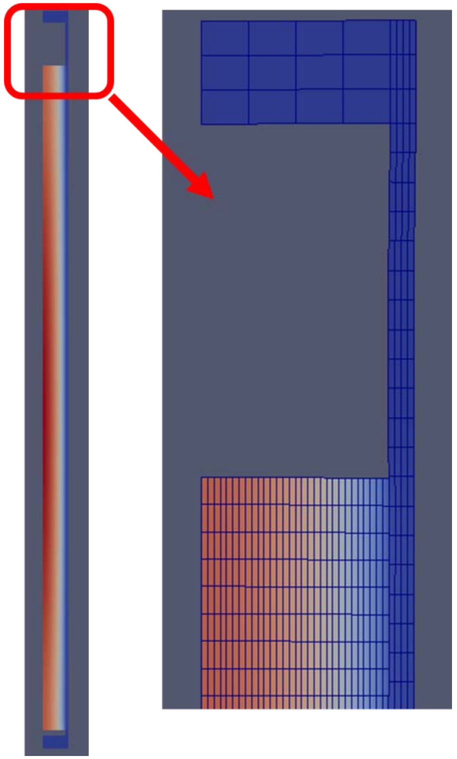




BISON Demonstration

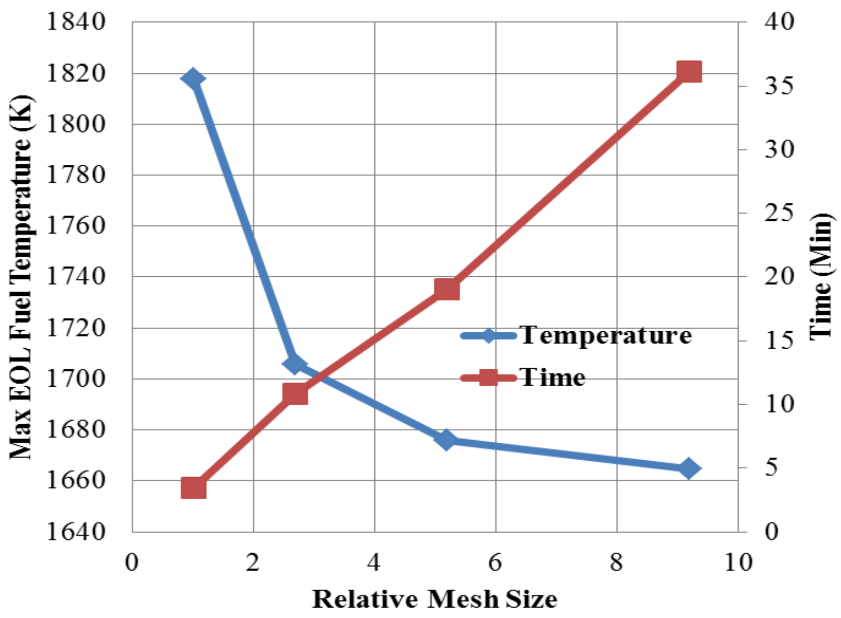
- In fuel performance, the height of the fuel rod can be properly scaled such that all the main performance parameters will be very close for the 10 pellet problem to a nominal fuel rod at ~ 370 cm.

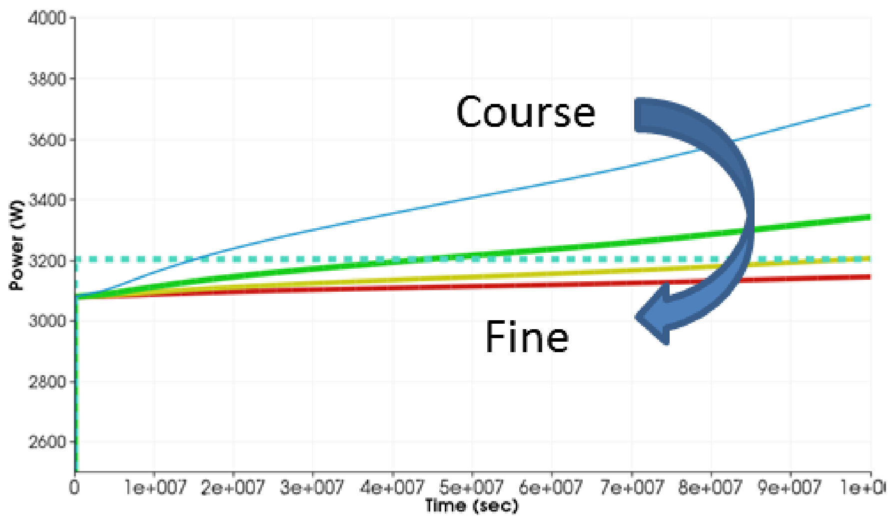
Design	Zirc	Annular	Units
Fuel Inner D	--	2.6	mm
Fuel Outer D	8.2	8.2	mm
Clad Inner D	8.36	8.36	mm
Clad Outer D	9.48	9.48	mm
Pitch	12.6	12.6	mm
Density	95	95	%
Length	11.86	11.86	cm
Axial Power	Cosine w/ 1.06 Peaking Factor		
LHGR History	27	27	kW/m
Total Time	1245	1245	Days
Discharge Bu	69.6	76.9	MWd/kgU

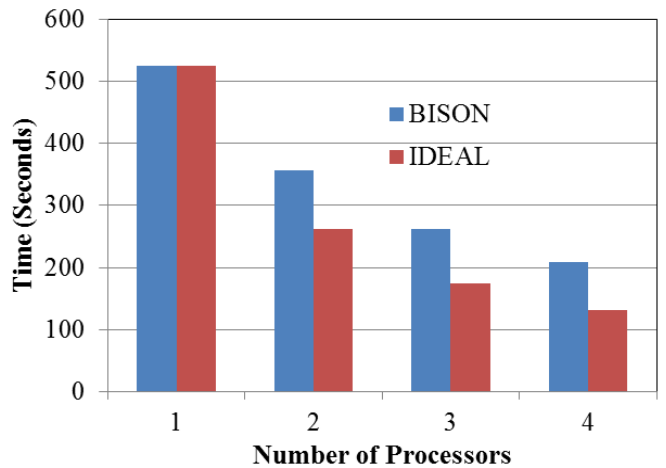


BISON Performance Assessment

- FRAPCON runtime is less than a second







Acknowledgement

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